A note on Charmed and Bottomed Pentaquark Production by Fragmentation

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H1 Collaboration recently observed the charmed pentaquark. In this short note, we point out that the dominant production mechanism for pentaquark consisting of a heavy quark is heavy quark fragmentation. We obtain a crude estimate on the fragmentation probability for charm quark into Θ_c^0, based on the known fragmentation probabilities of charm quark into mesons and baryons: $f(\bar{c} \to \Theta_c^0) \simeq (2-7) \times 10^{-3}$. Similarly, we also obtain the fragmentation probability for bottom quark into Θ_b^+: $f(\bar{b} \to \Theta_b^+) \simeq (5-20) \times 10^{-3}$. We also estimate the prospect of observing Θ_c^0 and Θ_b^+ at HERA, LEP, and Tevatron.

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I. INTRODUCTION

H1 Collaboration recently reported the discovery of a charmed pentaquark Θ_c^0 [1, 2]. This is the first evidence of pentaquark consisting of a heavy (anti-)quark, following the excitement of $\Theta^+(1540)$ in 2003 [3]. The interpretation of the observed charmed pentaquark follows closely along with the Θ^+, with the $\bar{s}$ replaced by $\bar{c}$.

In the constituent quark model, it is believed that the $\Theta^+(1540)$ consists of $\bar{s}uudd$. There are various possible configurations for this complicated system. Jaffe and Wilczek (JW) [4] interpreted the bound state as a diquark-diquark-antiquark structure. Each diquark pair is in the $\bar{\mathbf{3}}_c$ representation of $\mathrm{SU}(3)_c$ (analogous to an antiquark) and in the spin state $S=0$. Thus, the two diquark pairs combine in a P-wave orbital angular momentum to form a state with $\mathbf{3}_c$ in color, spin $S=0$, and $\bar{\mathbf{6}}_f$ in flavor. Then, combining with the antiquark to form a flavor antidecuplet and octet with spin $S=1/2$. The Θ^+ is at the top of the antidecuplet and has an isospin $I=0$. On the other hand, Karliner and Lipkin (KL) [6] interpreted the bound state as a diquark-triquark (ud)-$(ud\bar{s})$ structure. The first stand-alone (ud) diquark pair is in a state of spin $S=0$, color $\bar{\mathbf{3}}_c$ and flavor $\bar{\mathbf{3}}_f$ while the second (ud) diquark pair inside the cluster $(ud\bar{s})$ is in a state of spin $S=1$, color $\mathbf{6}_c$ and flavor $\bar{\mathbf{3}}_f$. The triquark cluster is then in a state of spin $S=1/2$, color $\mathbf{3}_c$ and flavor $\bar{\mathbf{6}}_f$. So the overall configuration will give a color singlet, spin $S=1/2$, and a flavor octet and antidecuplet. This internal configuration of KL is different from that of JW, as the diquark pairs in the JW configuration are symmetric while those pairs in the LK configuration are asymmetric. The present author [7] examined these two internal structures using color-spin hyperfine interactions, and found that the diquark-diquark-antiquark structure is slightly favorable in terms of hyperfine interaction. However, there could also be a mixing between these two configurations.

The diquark-diquark-antiquark picture of Jaffe and Wilczek [4] can be easily extended to charmed pentaquark, with the replacement $\bar{s} \to \bar{c}$. Since the charm quark does not belong to the $\mathrm{SU}(3)_f$ of (u,d,s), the internal quark configuration of Θ_c^0 will follow the configuration of the diquark-diquark subsystem. The masses of the charmed and bottomed pentaquark were also estimated using various methods [4, 5, 6, 7, 8]. Jaffe and Wilczek [4] estimated the mass of Θ_c^0 to be 2710 MeV, Sasaki [5] using lattice QCD estimated the Θ_c^0 to be about 640 MeV above the DN threshold, Karliner and Lipkin [6] gave a value of 2985 ± 50 MeV, Cheung [7] estimated the mass to be between 2938 and 2997 MeV, and Chiu and Hsieh using the lattice gauge method [8] obtained a value of 2977(109) MeV. [1] The latter three estimations are about 100 MeV, which is of the order of the uncertainty in the method of estimation, below the experimental value of 3099 MeV [1].

Unfortunately, another collaboration, ZEUS, at HERA so far has not reported any positive evidence for the charmed pentaquark [2]. While we are still waiting for further data, it is timely to point out that the dominant production mechanism for pentaquarks consisting of a heavy (anti-)quark is heavy quark fragmentation, similar to the production of heavy-light mesons and baryons consisting of a heavy quark. In this note, we obtain an estimate on the fragmentation probability for a heavy quark into a pentaquark. Using the probabilities we can then estimate the production rates at various collider environments, like HERA, LEP, and Tevatron.

The organization is as follows. In the next section, we estimate the fragmentation probabilities. In Sec. III, we estimate the production rates of Θ_c^0 and Θ_b^+ at HERA, LEP, and Tevatron. We summarize in Sec. IV.

[1] Stewart, Wessling, and Wise [9] had estimates on the mass of the S-wave charmed pentaquark T_s and the S-wave bottomed pentaquark R_s, which are below the strong decay thresholds.

II. ESTIMATES OF FRAGMENTATION PROBABILITIES

A naive estimate of the Θ_c^0 mass is as follows. The difference between Λ_c and a constituent charm quark (one half of J/ψ) is that Λ_c has an additional ud diquark. The constituent mass of this diquark is $M_{(ud)} \equiv M_{\Lambda_c} - M_\psi/2 = 736.47$ MeV. The constituent content of Θ_c^0 has one more diquark than Λ_c, and thus the mass of Θ_c^0 is $M_{\Theta_c^0} = M_{\Lambda_c} + M_{(ud)} =$ 3021.4 MeV, which is amazingly close to previous estimates [6, 7, 8] and the observed value by H1 [1]. We can use the same naive method to obtain the estimate for the mass of Θ_b^+: $M_{\Theta_b^+} = M_{\Lambda_b} + (M_{\Lambda_b} - M_\Upsilon/2) = 6518$ MeV, which is within 100 MeV uncertainty of our previous estimate based on color-spin hyperfine interaction [7].

Such an agreement between the naive estimate and the observed value may suggest that the dominant production mechanism for Θ_c^0 and Θ_b^+ is the same as Λ_c^+ and Λ_b^0, respectively, i.e., by heavy quark fragmentation. Let us first focus on estimating the fragmentation probability $f(\bar c \to \Theta_c^0)$, then repeat the exercise for $f(\bar b \to \Theta_b^+)$. The fragmentation probability for the charm quark into D mesons, summing over D^0 and D^+ is [10]

$$f\left(c \to (c\bar u), (c\bar d)\right) \simeq 0.781 \pm 0.023 ,$$

which implies the average

$$f(c \to c\bar q) \simeq 0.39 \pm 0.012$$

for one flavor of light quark q. We can then compare the probability into a diquark (dq) and a single quark as

$$\frac{f(\bar c \to \bar c(dq))}{f(\bar c \to \bar c q)} = \frac{f\left(c \to c(ud)\right)}{f(c \to c\bar q))} = \frac{0.076 \pm 0.007}{0.39 \pm 0.012} = 0.195 \pm 0.019 ,$$

where we have used $f(c \to c(ud)) = f(c \to \Lambda_c^+) = 0.076 \pm 0.007$. Therefore, the fragmentation probability for $\bar c \to \Theta_c^0$ is

$$\begin{aligned} f\left(\bar c \to \bar c(ud)(ud)\right) &= f\left(\bar c \to \bar c(dq)(dq)\right) \\ &= f(\bar c \to \bar c q \bar q) \times \frac{f(\bar c \to \bar c(dq))}{f(\bar c \to \bar c q)} \times \frac{f(\bar c \to \bar c(dq))}{f(\bar c \to \bar c q)} \\ &= (2.89 \pm 0.82) \times 10^{-3} . \end{aligned} \tag{1}$$

This is the prediction by the method I. An alternative way of thinking (method II) is a two-step fragmentation process:

$$f(\bar c \to \bar c(ud)(ud)) = f(\bar c \to \bar c ud) \times f((\bar c ud) \to (\bar c ud)ud) = (0.076 \pm 0.007)^2 = (5.78 \pm 1.06) \times 10^{-3} . \tag{2}$$

These two ways of visualizing the fragmentation process give consistent probabilities within a factor of two. We therefore take the range to be

$$f(\bar c \to \Theta_c^0) \simeq (2 - 7) \times 10^{-3} , \tag{3}$$

which is obtained by considering -1σ from the lower value and $+1\sigma$ from the upper value. In the H1 pentaquark paper [1], they also mentioned that the fraction of Θ_c^0 is roughly 1% of the total D^* production, which means

$$f_{\rm exp}(\bar c \to \Theta_c^0) \simeq 10^{-2} \times f(c \to D^*) = 2.35 \times 10^{-3} , \tag{4}$$

where we have used $f(c \to D^*) = 0.235$ [10].

We can now repeat the above exercise for the bottom quark. The method I gives

$$\begin{aligned} f(\bar b \to \Theta_b^+) &= f(\bar b \to \bar b(dq)(dq)) \\ &= f(\bar b \to \bar b q \bar q) \times \frac{f(\bar b \to \bar b(dq))}{f(\bar b \to \bar b q)} \times \frac{f(\bar b \to \bar b(dq))}{f(\bar b \to \bar b q)} \\ &= (1.09 \pm 0.56) \times 10^{-2} , \end{aligned} \tag{5}$$

where we have used $f(\bar b \to \bar b q) = 0.388 \pm 0.013$, $f(b \to b-\text{baryon}) = 0.118 \pm 0.02$ [11]. Using the method II, we obtain

$$f(\bar b \to \Theta_b^+) = (f(b \to b-\text{baryon}))^2 = (1.39 \pm 0.47) \times 10^{-2} . \tag{6}$$

Thus, the estimated range is

$$f(\bar b \to \Theta_b^+) = (5 - 20) \times 10^{-3} . \tag{7}$$

Note that in our estimate $f(\bar b \to \Theta_b^+) > f(\bar c \to \Theta_c^0)$. This is easy to understand, because the heavier b quark can extract the light quarks from the vacuum easier than the charm quark. Thus, in this sense the chance of forming Θ_b^+ is easier than forming Θ_c^0.

III. PRODUCTION RATES

Once we are equipped with the fragmentation probabilities we are ready to calculate the production rates of Θ_c^0 and Θ_b^+ at various collider environments. The cross section for Θ_c^0 is given by

$$\sigma(\Theta_c^0) = \sigma(\bar{c} + X) \times f(\bar{c} \to \Theta_c^0) \;, \tag{8}$$

and a similar formula for Θ_b^+.

At the HERA ep collider, the dominant production channel for heavy quarks is $\gamma^* g \to Q\overline{Q}$ where $Q = c$ and b. H1 Collaboration has measured the open charm production [12] in the kinematic region: $2 < Q^2 < 100$ GeV^2, $0.02 < y < 0.7$, and with $1.5 < p_T(D^{*\pm}) < 15$ GeV and $|\eta(D^{*\pm})| < 1.5$, the cross section $\sigma(D^{*\pm}) \simeq 8$ nb. Then, we can obtain the inclusive $\sigma(c + X$ and $\bar{c} + X) = \sigma(D^{*\pm})/f(c \to D^{*\pm}) = 8\,\mathrm{nb}/0.235 = 34$ nb. Thus, the cross section for Θ_c^0 is

$$\sigma(\Theta_c^0) = 34\,\mathrm{nb} \times (2-7)\cdot 10^{-3} = 68 - 240 \text{ pb} \;, \tag{9}$$

using Eq. (3). H1 [1] with a luminosity of 75 pb^{-1} observed 50.6 ± 11.2 signal events, from which the observed D^*p resonance is estimated to contribute roughly 1% of the total D^* production in the kinematic region studied. The detection efficiency is then of the order of $O(1\%)$ or less.

We can then proceed to the open bottom quark production at HERA. A recent measurement by ZEUS [13] gives $b\bar{b}$ production in the kinematic region: $Q^2 > 2$ GeV, $0.05 < y < 0.7$ with one of the b quarks hadronizing into a jet and the other B decaying into a muon:

$$\sigma_{b\bar{b}}(ep \to eb\bar{b} + X \to ej\mu + X) = 40.9 \pm 5.7\,^{+6.0}_{-4.4} \text{ pb} \;.$$

Note that the branching ratio $B(B \to \mu\bar{\nu}_\mu X) = 10.38\%$ [11], and we assume that hadronization into a jet is 100%. We can obtain the total $b\bar{b}$ cross section

$$\sigma(ep \to eb\bar{b} + X) = 394\,^{+80}_{-69} \text{ pb}$$

Thus, the production cross section for Θ_b^+ is

$$\sigma(\Theta_b^+) = 2 - 8 \text{ pb} \;, \tag{10}$$

using Eq. (7). With a luminosity of $O(100)$ pb^{-1} but an efficiency of the order of 1% or less (see above for Θ_c^0 detection), the number of Θ_b^+ that would be observed is less than 10 events. Therefore, the prospect of observing Θ_b^+ at HERA is not good.

We now turn to LEP Z data. With a total more than 10 millions hadronic Z decays collected by all four collaborations at LEP, the prospect of observing Θ_c^0 and Θ_b^+ is in fact quite feasible. In addition, the number of raw $b\bar{b}$ events is slightly more than $c\bar{c}$. Using 10^7 hadronic Z decays and $R_c = 0.1720 \pm 0.0030$ and $R_b = 0.21638 \pm 0.00066$ [14], the number of raw Θ_c^0 and Θ_b^+ is about $3400 - 12000$ and $11000 - 43000$ events, respectively. Therefore, even with an efficiency less than 1% the chance of observing Θ_c^0 and Θ_b^+ is very optimistic, especially Θ_b^+.

We can also estimate the production rates at the Tevatron. A recent published result [15] measured the production rates of D^0, D^{*+}, D^+, and D_s^+ at $\sqrt{s} = 1.96$ TeV:

$$\begin{aligned}
\sigma(D^0, p_T > 6\,\mathrm{GeV},\ |y| < 1) &= 9.4\ \mu\mathrm{b} \\
\sigma(D^{*+}, p_T > 6\,\mathrm{GeV},\ |y| < 1) &= 5.2 \pm 0.1 \pm 0.8\ \mu\mathrm{b} \\
\sigma(D^{+}, p_T > 6\,\mathrm{GeV},\ |y| < 1) &= 4.3 \pm 0.1 \pm 0.7\ \mu\mathrm{b} \\
\sigma(D_s^{+}, p_T > 8\,\mathrm{GeV},\ |y| < 1) &= 0.75 \pm 0.05 \pm 0.22\ \mu\mathrm{b} \;,
\end{aligned}$$

where we do not give the error for the D^0 case because we do not understand how they summed the errors of all the p_T bins. We then use the fragmentation probability of charm quark into D^0, D^+, and D^{*+} to convert the above cross sections into the total charm quark cross section $\sigma(c + X) \sim 20$ μb. Thus, the production cross section for Θ_c^0 is in the range

$$\sigma(\Theta_c^0) = (4 - 14) \times 10^4 \text{ pb} \;. \tag{11}$$

The expectation for a luminosity of $O(100)$ pb^{-1} and an efficiency of the order of 1% is in the range of $(4 - 14) \times 10^4$ events of Θ_c^0. Thus, there is a good chance of observing Θ_c^0 even the efficiency is further worsen.

We can also estimate the production rate for Θ_b^+ at the Tevatron. We found a recent published result on B^+ production at $\sqrt{s} = 1.8$ TeV [16]:

$$\sigma(B^+, p_T > 6 \text{ GeV}, \ |y| < 1) = 3.6 \pm 0.4 \pm 0.4 \ \mu\text{b} ,$$

which can be converted to raw $\bar{b} + X$ quark cross section by dividing the cross section with $f(\bar{b} \to B^+) = 0.388 \pm 0.013$ [11], and we obtain $\sigma(\bar{b} + X) = 9.3 \pm 1.5 \ \mu$b. Therefore, the estimated range of Θ_b^+ cross section is

$$\sigma(\Theta_b^+) = (4 - 20) \times 10^4 \text{ pb} . \tag{12}$$

The expectation for a luminosity of $O(100)$ pb^{-1} and an efficiency of the order of 1% is then in the range $(4-20) \times 10^4$ events of Θ_b^+. Again, the chance of observing Θ_b^+ at the Tevatron is very good even the efficiency is further worsen.

IV. CONCLUSIONS

In this note, we have pointed out that the dominant production mechanism for pentaquark consisting of a heavy quark is heavy quark fragmentation, similar to heavy-light mesons and baryons consisting of a heavy quark. Based on the known measurements of the probabilities of charm quark or bottom quark into mesons and baryons, we have estimated the fragmentation probabilities for $\bar{c} \to \Theta_c^0$ and $\bar{b} \to \Theta_b^+$, as given by $f(\bar{c} \to \Theta_c^0) \simeq (2 - 7) \times 10^{-3}$ and $f(\bar{b} \to \Theta_b^+) \simeq (5 - 20) \times 10^{-3}$. The Θ_c^0 has been observed at HERA, but the prospect of observing Θ_b^+ at HERA is not good. On other hand, the predicted number of events for Θ_c^0 and Θ_b^+ at LEP and at the Tevatron should be large enough for them to be discovered.

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